Frequently Asked Questions: Diffusion-Weighted Imaging (DWI)

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Background
MR diffusion-weighted imaging (DWI) has ceased to be used only in brain applications for several years. The utilization of whole body DWI is becoming a standard application in routine imaging. Whole body DWI has become as valuable as T2 contrast in tumor imaging and it allows to characterize tissue properties. Due to the more frequent use of DWI, questions are often asked with regard to the background, application, and interpretation of whole body DWI and its calculated Apparent Diffusion Coefficient (ADC) images. The following will answer some of these questions.

What is diffusion?
Molecular diffusion is the random movement of molecules – in our case water (H2O) – within tissues propelled by thermal energy. The contribution of intra- and extra-cellular (interstitial) movement to the total diffusion is still under investigation.

How is MR sensitizing the tissue for diffusion effects?
Within the spin echo preparation period of an EPI sequence, two strong gradient pulses are played out around the 180° pulse. The first pulse dephases the magnetization of moving and static spins and the second pulse rephases only static spins 100% while moving i.e. diffusing spins acquire non-zero phase dispersion, resulting in a stronger signal dampening of tissues with fast diffusion compared to tissues with slow diffusion. Free water experiences the strongest signal attenuation at higher b-values.

What does the b-value mean?
The b-value identifies the measurement’s sensitivity to diffusion and determines the strength and duration of the diffusion gradients. It combines the following physical factors into one b-value and is measured in s/mm² [1].

\[ b = \gamma^2 G^2 \delta^2 (\Delta - \delta/3) \]

The signal ratio diffusion-weighted to non diffusion-weighted signal is:

\[ \frac{S}{S_0} = e^{-\gamma^2 G^2 \delta^2 (\Delta - \delta/3) D} = e^{-bD} \]

- \( S_0 \) – signal intensity without the diffusion weighting
- \( S \) – diffusion-weighted signal
- \( \gamma \) – gyromagnetic ratio
- \( G \) – amplitude of the two diffusion gradient pulses
- \( \delta \) – duration of the pulses
- \( \Delta \) – time between the two pulses
- \( D \) – diffusion coefficient is a measure of the strength (velocity) of diffusion in tissue. The stronger the diffusion, the greater the diffusion coefficient, i.e. the ADC in our in vivo case. If you choose the b-value the reciprocal magnitude of the expected ADC (D) in the focus tissue you make the exponent of the exponential function being ‘-1’. This means your signal \( S \) is reduced to about 37% of its initial value \( S_0 \).

What is the optimum b-value?
A b-value of zero delivers a T2-weighted EPI image for anatomical reference. The b-values should attenuate the healthy background tissue more than the lesion at a level so that the intensity differences are about a factor of two at a comfortable signal-to-noise ratio (SNR) level i.e. there is signal left in the highest b-value image. In the range of clinically-relevant b-values (up to approximately 1,000), then the greater the b-value, the stronger the diffusion weighting and the higher signal attenuation.
the contrast in pathogenic regions. Shown below are examples of three b-values: b 0, b 500, and b 1000 s/mm². The proper b-value has approximately 80% of the reciprocal ADC value of normal background tissue. Keep in mind that higher b-values may pronounce lesions even more at the price of poor SNR due to longer TEs and increased susceptibility. This can be compensated by increasing averages, which result in longer scan times. Changing the b-value immediately influences other parameters like minimal TE, slice thickness and FOV as well as maximum matrix at a given optimal bandwidth. Furthermore anisotropy of tissues, like white matter, also influences the choice [2].

Why are a minimum of three directions measured for each high b-value? Diffusion may be different in all three dimensions, like in white matter. Fibers exhibit longer free path in the longitudinal direction than perpendicular to it. The ADC images are therefore different depending on the sensitizing direction. This information is collected by applying diffusion gradients in all three dimensions. For example, in the case of commissures, diffusion is severely limited perpendicular to the fibers due to the surrounding myelin layer. In contrast, there are few or no limitations along the fibers. Anisotropy may have a strong effect on measurement results. To measure the diffusion strength independent of anisotropy, diffusion images of different orientation are measured and averaged.

Why should I measure three b-values for a DWI protocol when two would be enough for calculating ADC? While two b-values are sufficient for creating an ADC image, the selection of three b-values (b 0, b 500, b 1000) delivers a more accurate calculation of the ADC values. The lower SNR of the b 1000 images introduces a higher standard deviation of the ADC which is partially compensated by the median value of b500. Here is an example of two ADC images, the first acquired with three b-values and the second with two b-values.

What is a trace image? The ‘trace image’ displays the geometric averaging of all three directional measurements, resulting in trace-weighted images. It suppresses to some extent anisotropy information and focuses on differences in signal attenuation. Like the ADC map, the trace-weighted map shows the strength of the diffusion and not its orientation.

Why do we need ADC images, and what does the ‘A’ in ADC stand for? In addition to diffusion contrast, diffu-
How-I-do-it

sion images also have an overlaying T2 contrast. In regions with long T2, this can simulate reduced diffusion ("T2 Shine-Through"). These portions of the signal can be eliminated by calculating a pure diffusion coefficient.

The 'A' stands for apparent because we do not measure the pure diffusion coefficient (D or DC). In living tissue the diffusion process is superimposed by capillary pseudo diffusion and gross motion to which the MR measurement is also very sensitive.

How is the ADC calculated?
Having measured a set of at least 2 different b-value images (e.g., b 0 and b 1000 s/mm²) the system calculates pixel by pixel the ADC by linear regression. The ADC pixel values together form the ADC map. On a half logarithmic scale, the signal decay delivers a straight tilted line whose slope provides the ADC. The faster the signal decay the steeper the slope and the higher the ADC.

Why are some lesions typically brighter than the background brain tissue on the higher b-value image and darker on the ADC map?
Due to the nature of certain lesions and their missing perfusion, the cells swell and hinder a normal diffusion; i.e., the mean free path is shorter. Water molecules cannot move as far in the damaged tissue as in normal tissue. As a result, the ADC is lower and appears darker than the surrounding normal tissue.

Which benefit does the calculation of an exponential map deliver?
The exponential map or image is calculated by dividing the maximal b-value diffusion-weighted image by the b₀ image. Mathematically the exponential map displays the negative exponential of the ADC; it is a synthetic diffusion-weighted image without T2 'shine-through' effect. The contrast behaviour is similar to the high b-value image [3].

How do I get the ADC value out of my ADC image and what is the right unit?
Place a region of interest (ROI) on the ADC map and record the mean value in that ROI. A value of 850 intensity points is to be interpreted as 0.85 × 10⁻³ mm²/s. This is valid for software versions since syngo MR B13. Systems with A-level software (e.g., syngo MR A30) and syngo MR B11, a mean value of 85 delivers the result above.

There are many publications on DWI and ADC. But why are there so many different unit and digits used for ADCs?
Currently, there is no consensus about applied units in DWI. You will find all of the following units which are equal (syngo MR B13).

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<td>1.0 × 10⁻³ cm²/s</td>
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Why does the ADC have a unit of an area/time although diffusion occurs in all three dimensions?
By definition, the diffusion coefficient is defined as the product of 1/3 times medial velocity times mean free path: D = 1/3 * v * l

The unit is an area per time.

Why is there a lack of standardization for the choice of b-values in whole body DWI?
As a relatively new application body DWI is on its way to become a technique with recommended b-values and measurement conditions. See cited reference [4] for further information.

Why do most body and liver DWI protocols start with b-value 50 s/mm²?
The selection of a low b-value larger than zero provides suppression of large vessels which makes lesions more con-
spicuous. The calculation of the tissue 
ADC can be more accurate when start-
ing with even higher b-values like 100 or 
200 to omit the contribution of flow and 
micro vascular effects. Low b-values 
more often serve as anatomical reference. 
In software level *syngo* 
MR D11A and 
above you can delimit the b-values for 
ADC calculation on the body diffusion 
application card of the protocol.

Why do liver diffusion-weighted 
images look darker on 3T than 1.5T? 
The T2 and T2* relaxations times for 
liver tissue, and other tissues as well, are 
considerably shorter as the field strength 
increases The overall signal is therefore 
diminished at 3T, even at lower b-values, 
due to the relatively long echo times (TE) 
used in DWI [5].

Which new DWI features are intro-
duced with software version *syngo* 
MR D11A for MAGNETOM Aera and 
Skyra? 
There is a new 'body diffusion' applica-
tion card with many new applications: 
- diffusion scheme monopolar/bipolar 
- start ADC calculation for $b \geq \ldots$ 
- exponential ADC; no T2 shine-through 
- invert gray scale ("PET-like” image) 
- calculated image of artificial b-values 
  plus 
- choice of dynamic field correction 
- improved fat saturation schemes

What should I know when scanning 
liquids in phantoms with DWI 
sequences? 
Firstly, the liquids should not move in 
the phantom bottle. Flowing liquid in 
the phantom would cause artificially 
strong diffusion and results in low intensity 
DWI images with inaccurately long 
ADC values. 
Secondly, the diffusion coefficient is also 
strongly temperature dependent. Pure 
water has a diffusion coefficient of about 
$3 \times 10^{-3}$ mm²/s (exactly: 2.96) at body 
temperature of 37 °C (98.6 °F). Water of 
0 °C (32 °F) has a diffusion coefficient 
of $1.12 \times 10^{-3}$ mm²/s. This could serve as 
a standard for different machines.

Additional reading 
In addition to the comprehensive Siemens 
applications guide, "Diffusion/Perfusion 
Imaging", there is literature [6] available 
which covers neuro and body diffusion. 
(Listed according to year of publication): 
Derek K. Jones: Diffusion MRI: Theory, 
Methods, and Applications; Oxford 
University Press 
Bachir Taouli: Extra-Cranial Applications 
of Diffusion-Weighted MRI; Cambridge 
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Imaging: Applications in the Body; Springer 
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